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A STUDY OF BINOCULAR COLOR MIXTURE

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Abstract—Using an apparatus which presents simultaneously the components for binocular color mixing to each eye and an additive, comparison mixture of the components to both eyes, an investigation was made of the effects of stimulus size, exposure time, and surround on the frequency with which the observers reported matching binocular mixtures. A comparison of binocular with additive mixtures as a function of (1) their relative total luminances using equal binocular components and (2) variable binocular composition with constant total luminance was also carried out. A brief history of work on binocular color mixture has been included.

Résumé—Avec un appareil qui présente simultanément les constituants d'un mélange binoculaire de couleur dans chaque oeil ainsi qu'un mélange additif de comparaison vu par les deux yeux, on a recherché les effets de la dimension, de la durée, et de l'environnement du stimulus sur la fréquence avec laquelle les mélanges binoculaires sont perçus. On a aussi examiné la comparaison des mélanges binoculaires avec les mélanges additifs en fonction (1) de leurs luminances relatives totales pour des constituants binoculaires égaux et (2) de constituants binoculaires variables pour une luminance totale constante. On a inclus un bref historique du problème du mélange binoculaire de couleur.

Zusammenfassung—Ein Apparat, der gleichzeitig jedem Auge je eine Farbkomponente für binokulares Farbensehen und zum Vergleich eine additive Farbmischung aus beiden Komponenten anbietet, wurde dazu benutzt, um den Einfluss der Reizgrösse, der Darbietungszeit und des Umfeldes von der Häufigkeit der beobachteten binokularen Farbmischungen festzustellen. Ein Vergleich von binokularer und additiver Mischung wurde bei gleichen binokularen Komponenten und bei gleicher totaler Leuchtdichte als eine Funktion (1) der relativen totalen Leuchtdichte und (2) der variablen binokularen Komponenten ausgeführt. Vorangegangene Arbeiten über binokulare Farbmischungen werden einleitend kurz erwähnt.

THE binocular mixture of colors was first reported by Haldat in 1806, and the succeeding early literature on the subject was largely concerned with the authenticity of the phenomenon. While many investigators vouched for it, a few were able to achieve only such related effects as oscillation or the dominance of one of the components (SOUTHALL, 1924).

This early literature was summarized by Helmholtz and Hering, who, as was often the case, took opposite points of view on the question. From his unsuccessful attempts, Helmholtz (SOUTHALL, 1924) concluded that the alleged binocular mixtures were due to background induction, the absence of a uniocular comparison field, or the presence of afterimages. HERING (1864) believed that binocular mixture was always possible if certain precautions were taken: the colored areas should be small and the same in shape, contour differences should be minimized, the colors should be of equal brightness and not widely separate in hue; complementary colors could be mixed if they were unsaturated and dull.

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The demonstration devised by HECHT (1928) has become the standard method of binocular mixture. He placed a red (Wratten No. 29) and a green (No. 58) filter side by side at one end of a black box; at the other end was a white piece of cardboard. On looking at the cardboard through the filters, he saw a yellow square flanked by a green and a red square.

MURRAY (1939) argued that Hecht's results were vitiated by the particular red and green used. She rejected his conclusions on the grounds that (1) the filters were wide band yellow–green and yellow–red, (2) the intensity used was too high for this type of color filter, (3) the procedure favored the focusing power of the lens for yellow radiation and the fusion area fell within the *macula lutea*, the yellow-enhancing region of the retina and (4) no time limit was set for the observations, possibly allowing adaptation to cancel the red and green.

In reply to Murray's criticisms, PRENTICE (1948) repeated Hecht's procedure using sharp cut-off interference filters, three light levels and a short exposure time. He found that even when exposed for 2 sec at his lowest stimulus brightness, red and green combined binocularly to give a yellow comparable to a spot of light projected on the screen through a yellow interference filter. A long exposure time (30 sec or more) gave a better yellow.

Very few studies have investigated the extent to which the binocular mixture resembles the same mixture to a single eye. The first quantitative study was by TRENDELENBURG (1923). To achieve binocular mixture, he found it necessary to use a very small stimulus, often less than 30 min of arc, but he succeeded in combining spectral red and green to get a white resultant which was compared, from memory, to the monocular mixture. In this and a later study (1923), he found that a much smaller proportion of the shorter wavelength was required in the binocular stimulus.

ROCHAT (1922), on the other hand, found that in binocular mixtures a little less of the longer wavelength was required. He projected complementary colors to a surface on which there was a white comparison field. By appropriately converging his eyes, he was able to compare the binocular mixture with the comparison field as well as with a monocular mixture of the combined complements. Both blue and yellow as well as red and blue–green gave a match to white. He could not, however, obtain a binocular match within the region from 610 to 570 mμ.

LIVSHITZ (1940), with an optical system consisting of a spectroscope and a double monochromator, was able to present a comparison field of combined monochromatic colors to each eye while the color components for the binocular combination were presented to an adjacent area of each retina. The intensities of the monochromatic fields were photometrically balanced and the spectral region from 640 to 530 mμ was matched monocularly and binocularly at 10 mμ intervals by combining 670 and 517 mμ. From 640 to 580 there was close agreement between all the matches. From 570 to 540 much less red was needed in the binocular match. Thus, in the region where Trendelenburg found a difference between monocular and binocular red–green mixtures, Livshitz found close agreement. But the differences in the spectral green used and the mode of presentation of the comparison field may account for this.

The present study has investigated the effect of various experimental conditions on the binocular mixture of colors and has compared binocular mixtures to adjacent additive mixtures presented simultaneously.

APPARATUS

The color mixer used in this study presented simultaneously to each eye a circular bipartite field. In the upper half of each field appeared an additive mixture of two color

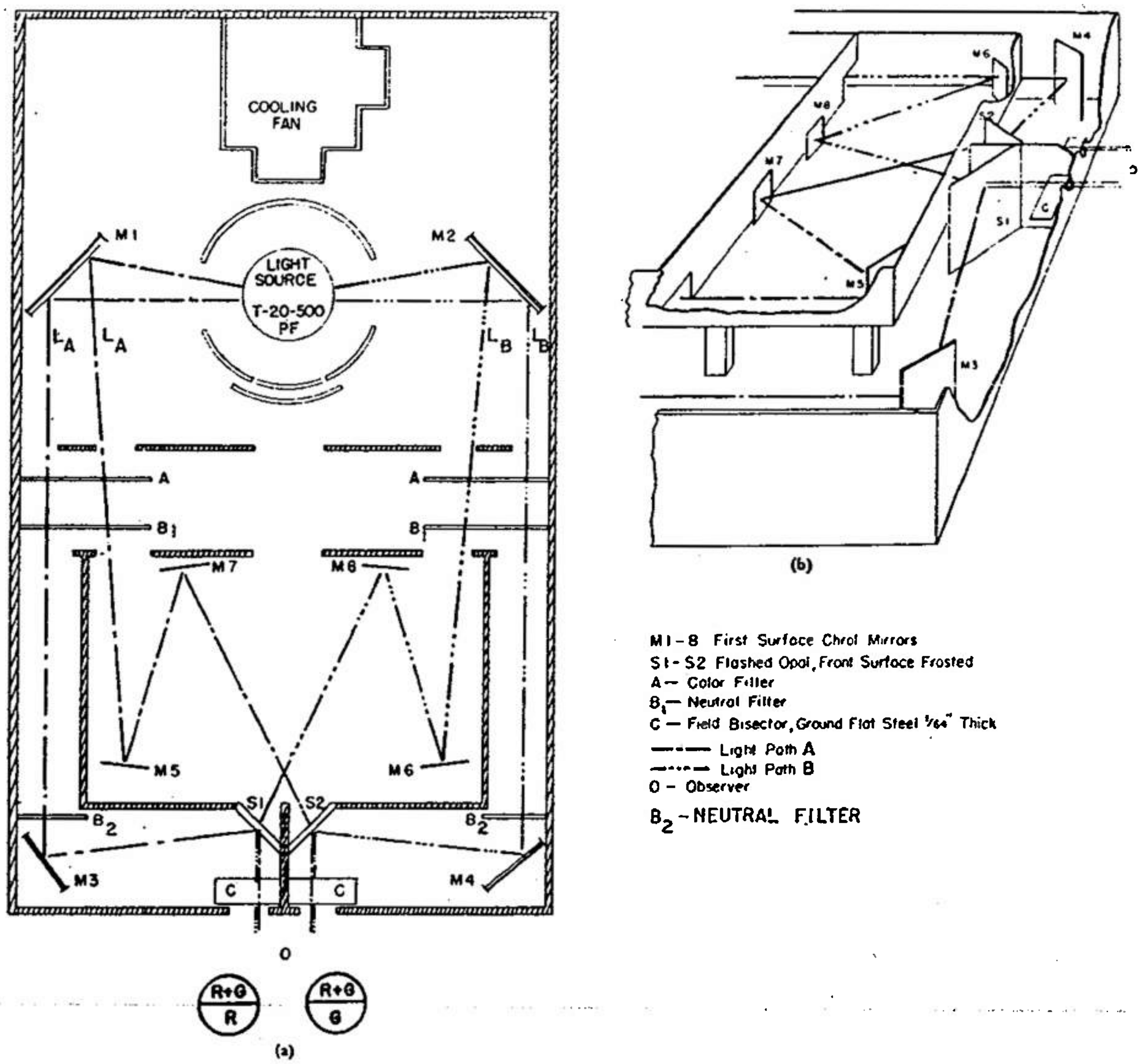

FIG. 1. Diagram of the apparatus.

components, which served as a standard or comparison mixture. In the lower half, one of the color components was presented to each eye for binocular mixture. The schematic drawings of the apparatus in Fig. 1(b) show how this was done. Light from a 500 W lamp of color temperature 3142°K was reflected by chroluminum mirrors, M_1 and M_2, through colored and neutral filters at A and B, after which it was split into two beams by pairs of mirrors at M_3 and M_5, or M_4 and M_6. One beam of each pair (i.e. from M_3 and M_4) was reflected to the whole area of the white diffusing screen (ground opal glass) at S_1 or S_2. The other beam (i.e. from M_5 or M_6) was reflected from mirrors M_7 or M_8, through the upper half of the opal glass screens at S_1 or S_2, to mix with the light from M_3 or M_4 falling on the front surface of the screen (see insert, Fig. 1). Thus a given color component of the stimulus mixture was reflected from the entire front surface of one diffusing screen and was trans-

mitted through the upper half of the other opal glass screen. One color was transmitted to the right eye and reflected to the left eye while the second color was reflected to the right eye and transmitted to the left eye. The mirrors and the glass opal screens were non-selective in the visible region of the spectrum.

Size of the stimulus was controlled by circular apertures set in front of the color mixing screens. The distance between the apertures was 2 in. center to center. The observer viewed the apertures from a distance of 18 in. through prisms held in a head-rest, which were adjusted to give precise registration of the binocular fields.

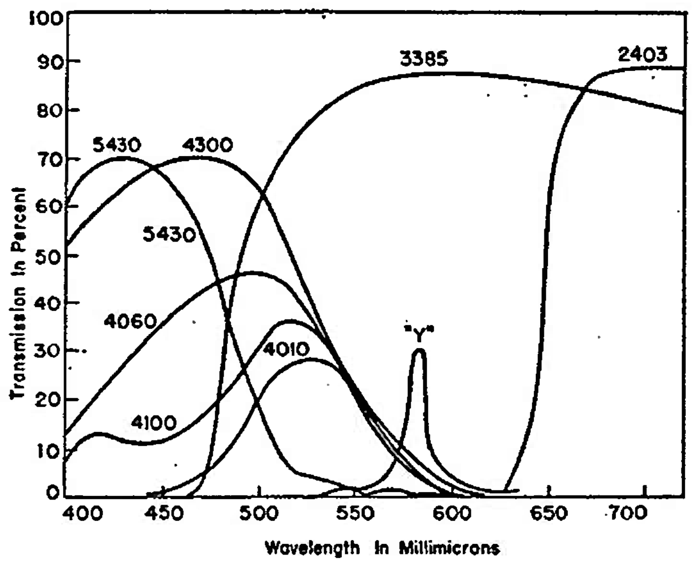

Fig. 2. Spectral transmission curves of the filters.

For a light surround, the white cardboard front of the apparatus was illuminated uniformly over an area subtending 20° visual angle by a Macbeth lamp (Illuminant C). The stimulus fields were occluded by a manually operated shutter on whose front were two luminous dots which served to orient and converge the eyes prior to stimulus presentation when a dark surround was used.

The maximum luminance of the beam reflected from the opal glass screen was 68 ft–L; that of the transmitted beam was 24 ft–L. The binocular mixture field and stimulus mixture field were equated for luminance by inserting neutral density filters in the appropriate light paths (i.e. at B_2).

The colors were produced by various Corning filters whose transmission curves are shown in Fig. 2. Their trichromatic specifications, dominant wavelength (λ) and purity (P) calculated for the light source of 3142°K color temperature, are given in Table 1.

PROCEDURE

The observer was seated with the head positioned by a head-rest. The bipartite stimulus fields were brought into register using the horizontal bisecting line as the alignment indicator. The observer was adapted to the surround brightness for five minutes, and given the following instructions: "At the signal 'now' a disk bisected by a horizontal line will be exposed. You are to judge whether the lower half of the disk is the same color as, or a different color

TABLE 1. SPECIFICATIONS OF THE COLOR FILTERS

Corning filter No.	x	y	Y	(λ)	P (%)
2403	0·728	0·272	0·029	655	1·00
3385	0·495	0·473	0·825	580	0·93
4010	0·248	0·633	0·116	539	0·72
4100	0·206	0·514	0·133	516	0·39
4060	0·195	0·403	0·159	500	0·38
4300	0·169	0·312	0·172	491	0·53
5430	0·150	0·103	0·032	471	0·84
Baird yellow "Y"	0·493	0·505	0·102	577	1·00

from, the upper half. If the lower half of the disk is a different color, report in what direction it differs."

Two seconds before the stimulus exposure, a ready signal was given. Rest periods were given after about thirty presentations.

1. PRELIMINARY EXPERIMENTS

An attempt was first made to ascertain the effect of the experimental conditions on binocular color mixture. Three stimulus variables were manipulated to determine their influence on the frequency with which such mixtures were reported, namely, stimulus size, exposure time, and surround brightness. The apparatus did not provide wide enough variations of stimulus intensity for complete investigation of this variable.

When a 5° stimulus field was used, the observers agreed that this area presented a mottled appearance which led them to confine their judgments to the center of the field. On this basis, a 2·5° stimulus was used in succeeding work and size appears as a variable only in the data of the preliminary experiment.

Five staff members (A. Morris, C. Pratt, J. Smith, E. Sandberg and R. Derby) with observing experience participated as observers in the preliminary work. All had normal color vision and wore spectacles for 20/20 vision when necessary. They were presented with stimuli produced with Corning glass filters of dominant wavelength 655 mμ (see Table 1) and 471 mμ paired with each other and each of them was paired with 539, 500, 516, and 491 mμ; 471 mμ was also paired with 580 mμ. The test pairs of stimuli were presented at five luminance levels in 0·1 density steps on the wedges; the test field was equal in luminance to the comparison field at the 0·3 density setting. They were first exposed for 2 sec in a 5° field with a surround which was either black or 10 per cent brighter than the stimulus. Next, 2·5° stimuli were presented under the two surround conditions for 6 sec. Each pair was presented at least thirty times in random order. A total of 3324 combinations was presented, 1662 under each surround condition, 1584 with the 2 sec exposure and 1740 with the 6 sec exposure.

The percentages of binocular color-mixtures matching the comparison field under the various conditions are given in Table 2. Increasing the exposure time from 2 to 6 sec produced five times as many binocular matches, while introducing a light surround reduced the number of matches by half for the 6 sec exposure time.

The composition of the binocular mixtures were averaged for all stimulus series in which six or more reports of "same" were given, and the percentage by which a binocular com-

ponent differed from the corresponding comparison component was computed. Some deviation of the binocular components from the comparison components was the rule. The average difference was less than 10 per cent, although the extreme difference was 53 per cent. The brightness of the surround showed no systematic effect on the composition of the binocular mixture.

TABLE 2. THE PER CENT OF PRESENTATIONS RESULTING IN BINOCULAR MATCHES UNDER VARIOUS EXPERIMENTAL CONDITIONS

Surround	Exposure Time		No. Presentations
	2 sec (5° field)	6 sec (2·5° field)	
Dark	3·4	31·0	1662
Light	5·1	13·5	1662
No. of presentations	1584	1740	3324

It is noteworthy that the mixtures containing a red component generally show that an excess of red is required in the binocular mixture, but the binocular mixtures with a blue component required an excess of blue. There was only one instance of a mixture with both red and blue and here an excess of red was required. These results are plotted in Fig. 3 and show how the mixtures with 655 mμ as one of the components deviate toward the red region of the diagram. It will be noted that matches were obtained in the region between 585 and 610 mμ where Rochat was unable to do so.

The observers reported that frequently the binocular field was not stable, but fluctuated. Unless a color mixture was observed immediately, there was either oscillation between the components or one of them dominated. The oscillation decreased with time, however, and it appeared likely that a longer exposure time would further increase the number of binocular mixtures.

It was difficult to account for the effects of surround illumination. Why should a dark surround produce an increase in the number of matches? The explanation may lie in the fact that the light surround could not be evenly illuminated beyond a 20° visual angle. This unevenness was minimized, however, in the succeeding work with a diffusing medium in front of the lamp and a light surround was used since it permitted a much shorter period of preadaptation.

2. VARIABLE TOTAL LUMINANCE AND EQUAL BINOCULAR COMPONENTS

Two observers were presented with 2·5° stimuli exposed for 15 sec. The filter with a dominant wavelength of 655 mμ was paired with 539 mμ and 471 mμ was paired with 577 mμ. The former pair was presented at five levels and the latter at six levels of total luminance, with the two components always equal to each other. Both pairs were presented at least ten times (ES received 20 presentations of the first pair) in random order for a total of 270 presentations. The luminance of the comparison mixture was 1·5 ft–L and that of the surround was 5 ft–L. The observers were instructed to make no judgment unless the binocular stimuli were fused for several seconds, long enough to make an accurate comparison between the two fields.

The responses were classified as (1) unqualified judgments of "same", (2) same but lighter, (3) same but darker, (4) oscillating and (5) one component dominates. These tabulations are shown in Table 3. In each series of combinations for both observers, the combination most closely resembling the comparison mixture was most frequently judged unqualifiedly the same. That is, the binocular mixture matched the comparison mixture when the total binocular luminance equalled the luminance of the comparison mixture to

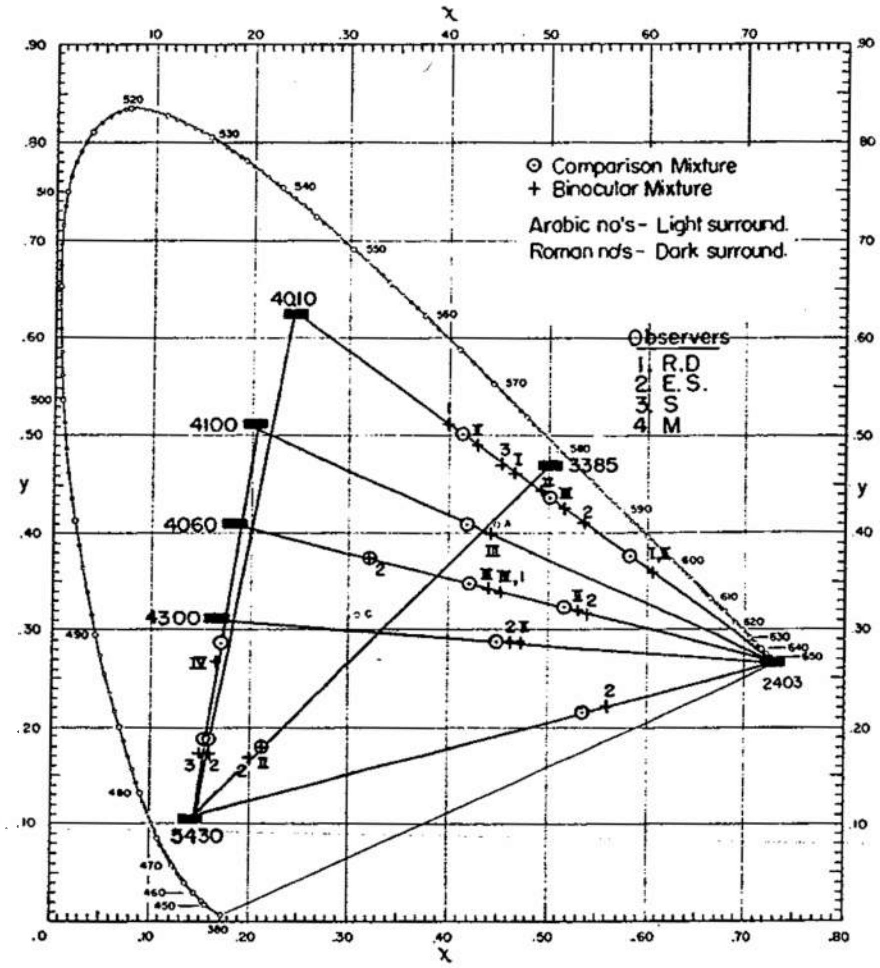

FIG. 3. Comparison of binocular and additive mixtures. The average chromaticities of the binocular mixtures for every series in which six or more reports of "same" were given compared to the chromaticities of the additive mixtures. Binocular mixtures with a red component usually required an excess of red.

only one eye. Since the comparison mixture, however, was presented to both eyes, this means that there was no summation of the two monocular fields. The luminance for two identical stimuli (one to each eye), then, is apparently not additive, while the luminances of two different stimuli, mixed binocularly, are additive.

Both observers more frequently judged the binocular mixture to be darker as it decreased in total luminance, but there were few reports of any mixture at all when the binocular

stimulus was brighter than the standard stimulus. Instead, this resulted in increasing oscillation. A darker binocular field, on the other hand, led to reports of dominance of one of the components.

Under these conditions, then, 33 per cent of the first pair of stimuli and 30 per cent of the second pair were judged unqualifiedly the same as the comparison mixture. An additional 19 per cent of the first pair and 35 per cent of the second pair were judged the same with qualifications. Thus, over half of the presentations resulted in binocular mixtures.

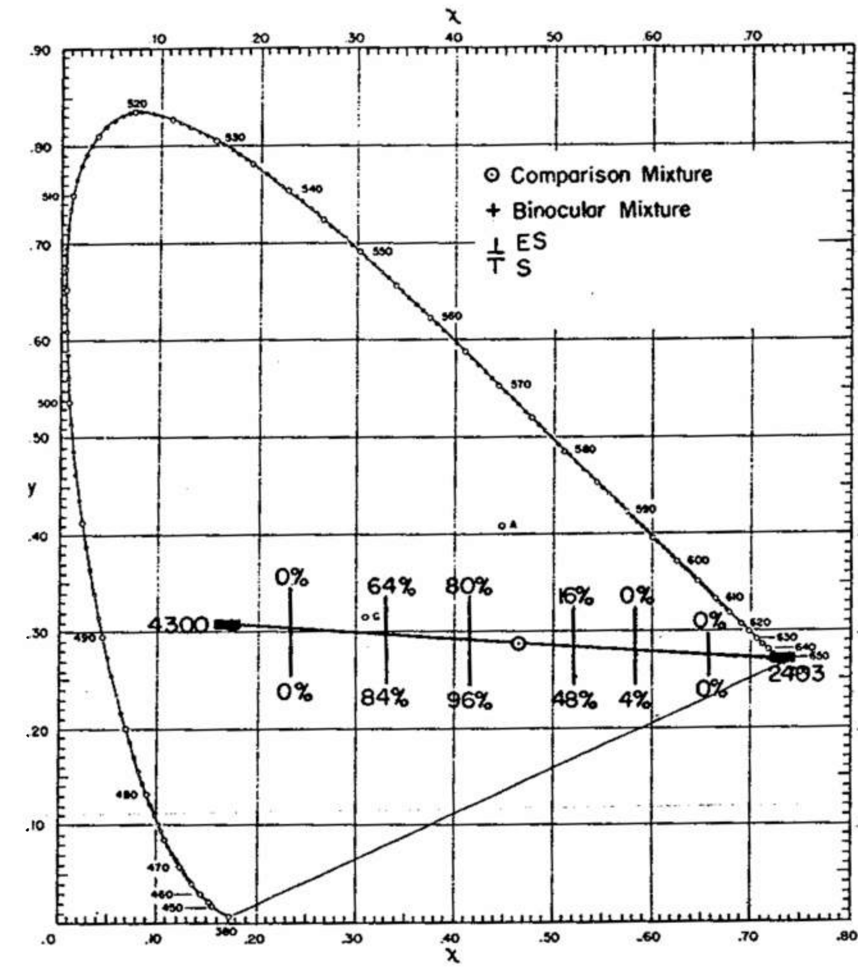

FIG. 4. The distribution of binocular match judgments. The per cent of "same" judgments for binocular mixtures of various compositions. The total luminance was constant.

The average value of the binocular components was computed for all unqualified judgments of "same" in each stimulus series. There was good agreement with the composition of the comparison mixture; the largest deviation was only 11 per cent. Thus with the exposure time increased from 6 to 15 sec and with a more even surround, the frequency of "same" responses increased and the disparity between the compositions of the comparison mixture and the average composition of the binocular mixtures judged the same decreased.

3. CONSTANT TOTAL LUMINANCE AND VARIABLE BINOCULAR COMPOSITION

Using the same procedure as outlined above, two observers were presented with the pairs 655–491 mμ and 471–577 mμ. The components in the comparison field were always epual to each other; but for the binocular field, six combinations of each pair were presented with varying proportions of the two components, with their total luminance constant. The luminance of the binocular components for the first pair ranged from 0·21 to 1·66 relative

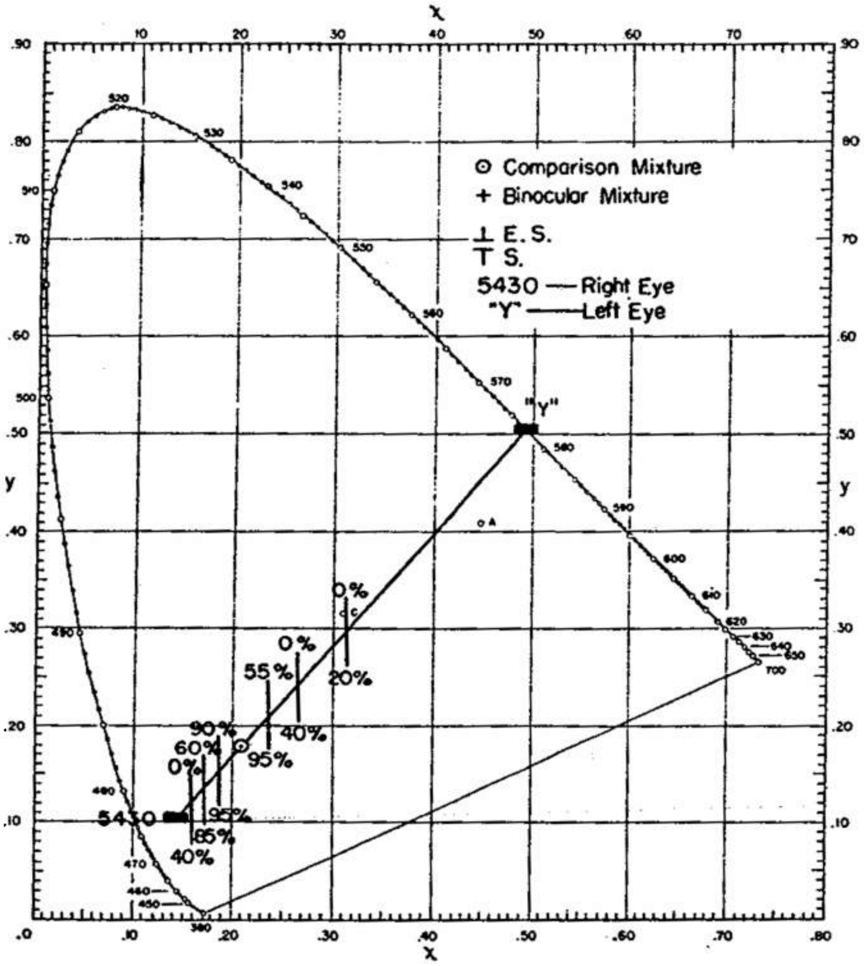

Fig. 5. The distribution of binocular match judgments. The per cent of "same" judgments for the binocular mixtures of various compositions. The total luminance was constant. Compare these values with those in Fig. 6 for which the binocular components were interchanged.

to the corresponding component in the comparison field and from 0·43 to 1·89 for the second pair. The total luminance of the first pair averaged 1·90$\pm$0·08; the second pair averaged 2·10$\pm$0·22. Each observer received 25 presentations of all combinations for the first pair and 20 presentations of all combinations for the second pair. In half the presentations of the latter, the component colors to each eye were interchanged.

No "same" judgments were reported at either extreme of the first series. As the composition of the binocular stimulus matched the comparison field more closely, the frequency of "same" reports increased, but the distribution of judgments is not symmetrical about the mode. As shown in Fig. 4, binocular combinations containing a larger amount of BG than R are more frequently judged the same than combinations with larger amounts of R.

Similar results were obtained with the second pair of stimuli, as shown in Figs. 5 and 6. Again the "same" judgments occurred more frequently as the binocular stimulus became more like the comparison field and again the combinations containing a larger amount of B evoked the most responses. For this pair, however, observer S gave some "same" judgments for the extreme combinations.

A comparison of Fig. 5 with Fig. 6 shows the changes occurring when the binocular components are interchanged. The modal point for ES shifted toward the blue, while that for S shifted markedly toward the yellow.[2]

Although the exposure time in the latter half of the study was 15 sec, the observers responded as quickly as possible and their response times were recorded and showed there was no simple relationship between response time and frequency of matches. The stimulus series with the highest frequency of matches corresponded to a rather short average response time, approximately 8 sec. Indeed, all the series with a high frequency of matches had short response times. These times tended to increase as the frequency of matches decreased. This may, of course, simply represent the confidence with which the reports were made.

DISCUSSION

These results show that binocular mixture of colors does not occur with every presentation. The frequency of such mixtures varies with the experimental conditions and the composition of the stimuli. Optimal conditions include a relatively long exposure time, a uniform surround, a small stimulus field and equal luminance of the two components; if the binocular stimulus is compared with a standard, the total luminance of both fields should be equal. If the conditions are not optimal, mixture will occur in fewer cases.

We have concluded that an "appropriate" exposure time is rather long, about 5 to 10 sec. If we must wait this long for the initial oscillation to cease before fusion occurs, does this indicate that no true mixture is taking place and that Helmholtz was correct in attributing the alleged mixtures to induction and afterimages etc.? We feel that such regularity of results as appears in Figs. 4, 5 and 6 argues against this interpretation. There does not seem to be any reason why small changes in the binocular components should affect the afterimages or the amount of background induction such that a greater frequency of matches would result. The marked relationship between the binocular composition and the frequency of matches in Figs. 4, 5 and 6 bespeaks actual color mixture. Since central processes are involved, long exposure times must be expected.

Our results indicate that, under certain conditions, the luminance of a binocular mixture may be the sum of its components. This has been a disputed point since FECHNER (1861) reported that if he placed a dark gray glass in front of one eye after looking at the sky with the other, the sky appeared darker when viewed binocularly. The effect of adding the reduced illumination to the one eye diminished the resultant total brightness. SHERRINGTON (1904–1905) subsequently found that monocular and binocular luminances were the same

[2] We have determined that the achromatic match point for S is considerably nearer the yellow region of the spectral locus than is the case for ES and, doubtless, these differences between observers and also between eyes are due, at least in part, to differences in macular pigmentation.

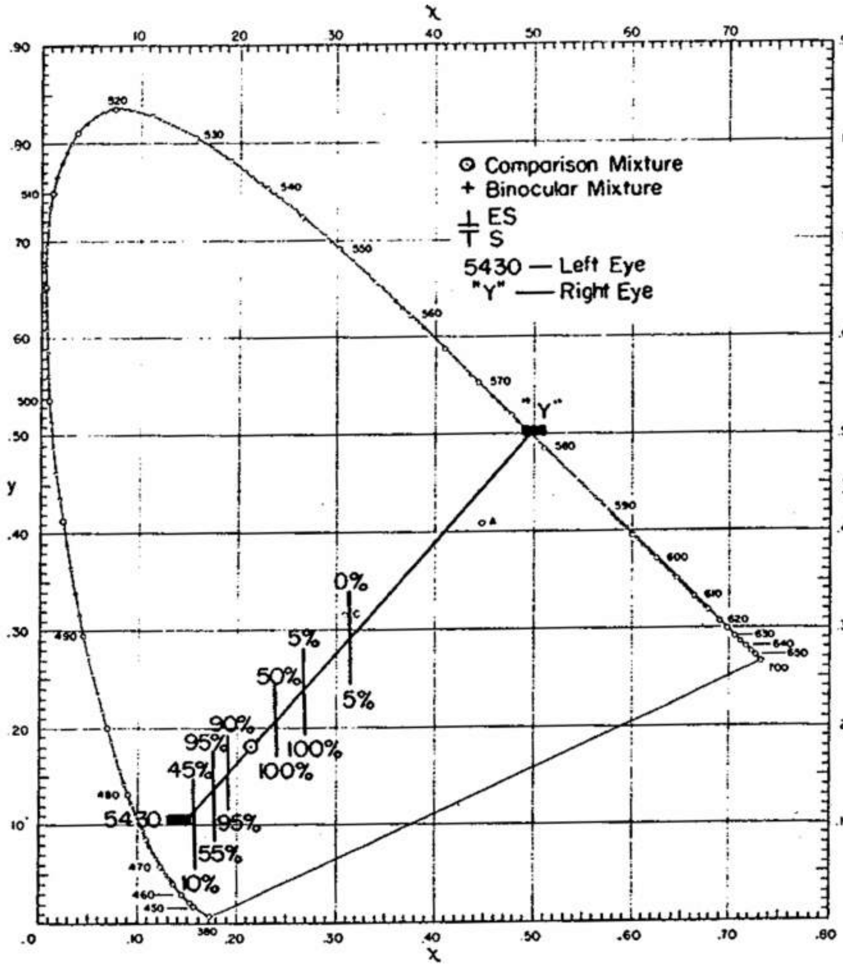

Fig. 6. The distribution of binocular match judgments. The per cent of "same" judgments for the same binocular mixtures as in Fig. 5 but with the components interchanged.

and concluded that there was little interaction between monocular and binocular vision. But Bartley (1941) criticized Sherrington's procedure and showed that monocular luminance is some value between equality and double that of the binocular luminance depending on the absolute luminance of the binocular field.

The present results show that the binocular mixture looked equal in brightness to the comparison (additive) mixture when the luminance of the binocular field equalled the luminance of either comparison field. That is, the total luminance of the two comparison fields was double the total luminance of the binocular fields. This appears to indicate that there is binocular summation of apparent brightness when the two fields are disparate but not when they are identical in hue.

The results in Part I, shown in Table 3, indicate that binocular mixtures with a red component required an excess of red to match the additive mixture. This supported Trendelenburg's results. But the results which are plotted in Figs. 4 and 5 indicate that less red was needed. The main difference between these two parts of the experiment is that in the

TABLE 3. FREQUENCY DISTRIBUTION OF JUDGMENTS FOR VARIOUS BINOCULAR COMBINATIONS

(a) Comparison field: 1·00 GY+1·00 R

Binoc. comb.		Judgments									
GY	R	Same		Lighter		Darker		Oscillation		Dominance	
		S	ES	S	ES	S	ES	S	ES	S	ES
0·77	0·77		1			10	5		1		13
0·86	0·86	3	4			6	5	1	1		10
0·97	0·97	9	14				1	1			5
1·19	1·19	8	11		1			2	6		2
1·35	1·35							10	16		4
(b) Comparison field: 1·00 PB+1·00 Y											
0·54	0·54					10					10
0·72	0·72	5				5	10				
0·91	0·92	8	4			2	5		1		
1·03	1·04	10	9				1				
1·43	1·43			6				4	7		3
1·77	1·77			3				7	8		2

former the luminance of the binocular field varied above and below the luminance of the comparison field. In the latter experiment, on the other hand, the two luminances were kept equal to each other. An explanation of the contradictory results may stem from a study of the red–green ratio as a function of luminance. DIMMICK and WIENKE (1958) have shown that the red–green ratio decreases as the luminance of the yellow standard increases. This decrease, furthermore, is not linear but is a negatively decelerating function. Thus, it follows that if, on the one hand, we have a red stimulus with a constant luminance and, on the other hand, a red stimulus whose luminance is varying about the comparison luminance, there will be an average net loss of its luminance in the latter case. The relative gain for the higher luminances will not completely offset the relative loss for the lower luminances. Thus we would expect to need an excess of red when the luminance of the stimulus is varied but not when it is constant.

CONCLUSIONS

1. The frequency of obtaining binocular color mixture varies with the experimental conditions and the composition of the stimuli.

2. Optimal conditions include an exposure time of 5 to 10 sec, a small stimulus field, uniform surrounds, and binocular components of equal luminance.

3. Binocular mixtures match an additive mixture with increasing frequency as the total binocular luminance is more closely equated to the additive luminance. When the binocular luminance is less than the additive luminance, there is a tendency for one of the binocular components to be dominant; when it is greater than the additive luminance, there are more reports of oscillation between the binocular components.

4. With the total binocular luminance equated to the additive luminance, but with variable binocular components, the greatest frequency of matches occurs when the two sets of components are comparable.

5. The luminance of a binocular mixture composed of two colors will match the luminance of the monocular mixture of these colors presented to one eye, but not the sum of the luminances of two such mixtures, one presented to each eye.

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